Chapter 15

UPHOLSTERED FURNITURE: PREDICTION BY CORRELATIONS

by

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INTRODUCTION

A detailed model for furniture combustion, of the sort described in the preceding chapter, represents the best-possible, state of the art calculation. For most purposes in design and evaluation, however, it is sufficient to obtain less accurate results, if they can be obtained by simple measurement techniques. In this Chapter we will examine large-scale measurements of heat release rates of upholstered furniture. Based on such measurements, we will introduce several techniques for predicting the essence of the full-scale behaviour by judicious use of bench-scale test results.

We will begin this Chapter with a brief review of some of the essential features of furniture burning in rooms. We will then proceed to three essential studies: the first, which we will call 'Conventional furniture,' will focus on work done at NIST during 1982-1984. In these studies, the burning behaviour of furniture intended to represent commonly used, store-bought furniture was examined. In the second series, which we will call 'Furniture of intermediate fire behaviour,' we will describe studies conducted at the Fire Research Station on furniture intended still intended for the domestic furniture market, but having improved fire performance. In the final study, which we shall refer to as 'Highly fire-retarded furniture,' we will examine furniture intended to satisfy regulatory requirements for institutional occupancies. In all three studies, we will see that the brief titles captioning the work are not strictly correct — specimens were also examined in each series of tests which were of better or worse performance than the main body of specimens. Nonetheless, it will be seen convenient to view the results in terms of such generic groupings.

We conclude this Chapter with a discussion of current standardized tests for heat release rate of furniture.

BACKGROUND

Furniture flammability studies have been pursued for many years at various institutions around the world. These studies typically focused on ignitability behaviour, and often were of a completely subjective nature. Since the scope of this book is heat release rate, we will consider only the HRR aspects of upholstered furniture fires. The majority of upholstered furniture fire deaths has statistically been shown in most countries to be due to smouldering, i.e. cigarette, ignitions. Thus, as early as 1976 [1] test methods were proposed to address this issue. The heat release rate behaviour of furniture, once ignited by a flaming source, is not correlated to its behaviour in resisting cigarette ignitions. It is possible to come up with constructions which are superior on both counts, but other types are available which perform well for cigarette ignitions but poorly for flaming sources, or vice versa.

The HRR behaviour of upholstered furniture could not be accurately examined until the development of the furniture calorimeter, although very crude estimates could be made from load cell data in earlier room fire tests. Thus, the first accurate study of upholstered furniture HRR behaviour was conducted in 1982 at the NIST laboratories [2]. Since then, quantitative upholstered furniture HRR studies have also been pursued at the Statens Provningsanstalt, in Borås, Sweden, and at the Fire Research Station, in Borehamwood, England. Before the furniture calorimeter data could be used and be considered as representative of furniture behaviour in room fires, it was necessary to demonstrate that the chair[1] HRR measured in the furniture calorimeter was the same (or uniquely related to) as measured in room fires. A preliminary study to determine this point was conducted; the results showed that measured values of HRR in the furniture calorimeter and in the room fire agreed up to quite high HRR rates [3]. Eventually, however, a room fire can reach flashover and subsequently become ventilation-limited [4]; such a relationship cannot hold for ventilation-limited post-flashover fires and, indeed, for these fires no predictive methods are yet available. The actual point at which the room fire results diverge from the furniture calorimeter results was further explored in the course of the studies of highly fire-resistant furniture, described later in this chapter.

All of the existing information on upholstered furniture flammability was evaluated in an NIST project which resulted in the publication of the *Fire Behavior of Upholstered Furniture* monograph in 1985 [5]. This monograph examines in detail quantitative aspects of cigarette ignition, flame spread, and other related fire phenomena. An update discussing regulatory activities in furniture flammability was published in 1989 [6].

[1] For simplicity, we will use often *chair* as synonymous with ***upholstered furniture***, except in those few cases where it will be made clear that larger seating articles, such as two-seaters, sofas, settees, etc., are being discussed. Some peripheral upholstered furniture, such as footrests (hassocks), have never been quantitatively examined.

CONVENTIONAL FURNITURE

The first studies conducted in the NIST furniture calorimeter used a series of chairs intended to represent common domestic furniture. The chairs were tested in the furniture calorimeter, ignited with a 50 kW gas burner, which simulated a burning plastic wastebasket, placed alongside the chair. Some chairs had conventional wood frames, while others had plastic frames. Specimens from the chairs were also tested in the cone calorimeter. The preparation of cone calorimeter samples from chairs requires certain precautions — the material is intrinsically a composite, and may also contain protective barriers or interliners. Bench-scale testing of the frame material is not appropriate — the influence of the frame material has to be accounted for by other means, as will be shown below. The actual furniture calorimeter measured values of peak HRR for these chairs ranging from 370 kW to 1990 kW for single chairs, and up to 3120 kW for a 3-seater. The padding in these chairs included cotton, FR cotton, ordinary polyurethane (PU), and FR PU foam conforming to the California T.B. 117 [7]. Fabrics included cotton and polyolefin. Details of these tests are given in [2].

Subsequently, a complementary series of tests was conducted in which a steel frame was used to create full-scale mockups. These were tested in the same furniture calorimeter and ignited with the same gas burner. The peak heat release rates ranged from 260 kW to 1460 kW for specimens using normal polyurethane (PU) foam, and FR PU foam conforming to California T.B. 117. The fabrics were polyolefin and cotton materials. A smaller number of samples were tested which used neoprene foams. These showed very low peak HRR values, from near-zero to 120 kW.

The specimens which contained neoprene foam failed to spread flame completely around the specimen and were excluded from the development of the predictive correlation. The remaining specimens, both real chairs and metal-frame mockups, were found to be predictable according to the following correlation:

$$\dot{q}_{fs} = 0.63\,\dot{q}''_{bs}\left[\begin{matrix} mass \\ factor \end{matrix}\right]\left[\begin{matrix} frame \\ factor \end{matrix}\right]\left[\begin{matrix} style \\ factor \end{matrix}\right] \qquad (1)$$

where $\dot{q}_{fs}$ is the full-scale peak HRR (kW); $\dot{q}''_{bs}$ is the bench-scale heat release rate (kW/m^2), determined as described below; the mass· factor = the total combustible specimen mass (kg),

$$frame\ factor = \begin{cases} 1.66 & for\ noncombustible frames \\ 0.18 & for\ charring\ plastic\ frames \\ 0.30 & for\ wood\ frames \\ 0.58 & for\ melting\ plastic\ frames \end{cases} \qquad (2)$$

and

$$\text{style factor} = \begin{cases} 1.0 \textit{ for plain, primarily rectilinear construction} \\ 1.5 \textit{ for ornate, convoluted shapes} \\ \textit{with intermediate values for intermediate shapes} \end{cases} \quad (3)$$

The frame factor and style factor deserve some further explanation. For the sequence charring plastic/wood/melting plastic, the frame factors simply reflect the tendency of these particular types of frames to contribute to the severity of the fire **during the time of peak burning.** This happens according to how well the frame can endure structurally without beginning a form of collapse where fresh fuel is exposed to the fire. The reason that the metal frames have a higher frame factor is due to an entirely different cause. For all of the combustible frames, the total combustible mass includes all of the frame mass. Most of the combustible frame mass becomes involved quite late in the fire, so the actual contribution is limited. For the metal frames, by contrast, there is no combustible frame mass. Therefore, all of the specimen's combustible mass is involved during active burning.

The style factor accounts for the observation that chairs with highly ornate designs show a higher peak HRR than do corresponding chairs with rectilinear styles. The details of the flame spread process have not been modeled, so far, to represent this phenomenon on anything but an empirical basis.

The success of the above correlation in predicting the actual furniture calorimeter measured values is shown in Figure 1. It can be seen to be satisfactory throughout the regime tested, from around 400 kW to over 3000 kW.

Determining of test conditions

The data in the above correlation were derived for the following conditions:

irradiance of 25 kW/m^2
averaging period for $\dot{q}''_{bs}$ of 180 s after ignition

It might well be asked, How were these conditions arrived at? Our knowledge of fundamental fire physics is not advanced enough that these conditions could have been set by fundamental considerations. Instead, an empirical approach was necessary, and will continue to be needed for the foreseeable future. The procedure was to test the bench-scale specimens at various irradiances (25, 30, 40, and 50 kW/m^2) and to average the data for various time periods post-ignition (60, 120, 180, 240, and 300 s). Also, the peak $\dot{q}''_{bs}$ data were examined. For each of the various combinations of test irradiance and averaging period a least-squares curve fit was computed. The coefficients of variation were then compared

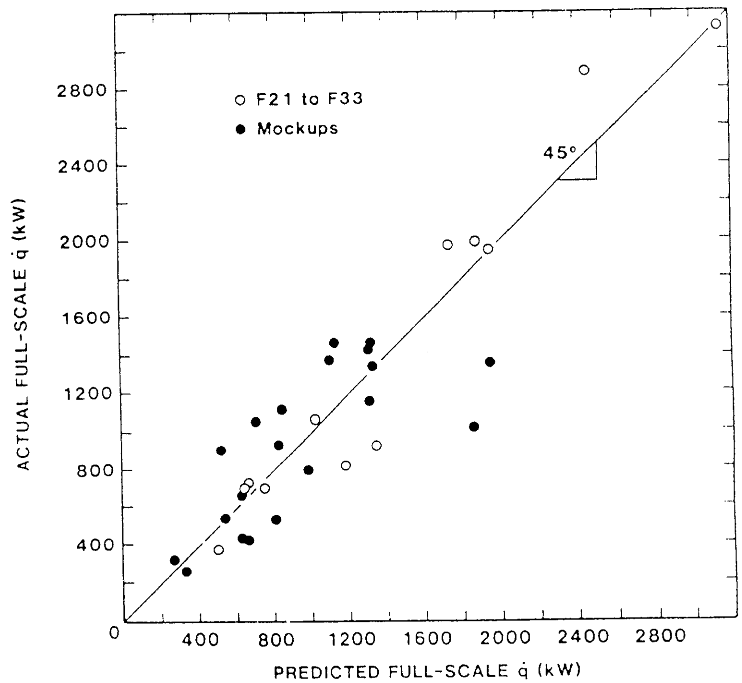

Figure 1. Predicted full-scale heat release rates, versus actual measured values

for all of these possibilities. The 25 kW/m^2 irradiance and 180 s averaging period were selected since the coefficient of variation was the smallest and therefore the prediction quality was optimal [8]. Typical Cone Calorimeter curves for two different specimens at two irradiances are shown in Figure 2. Specimen F21 had FR PU foam (CAL 117 type) and olefin fabric; while specimen F22 had FR cotton batting and cotton fabric.

Subsequent to this study, the emphasis shifted towards characterizing the fire performance of institutional, rather than domestic furniture. Preliminary explorations showed that for highly fire-retarded specimens testing at an irradiance of 25 kW/m^2 may not be desirable. Any heat release rate data are subject to much greater random scatter when taken at an irradiance only slightly higher than the minimum required for ignition. The minimum irradiance to ignite the rather common wool/neoprene combination in the Cone Calorimeter was found to be 14.5 kW/m^2 [5]; values higher than this can well be found for advanced FR constructions. Thus, a value of 35 kW/m^2 will be seen to be more appropriate for testing institutional furniture or the more highly fire-retarded domestic furniture that is discussed in the later.

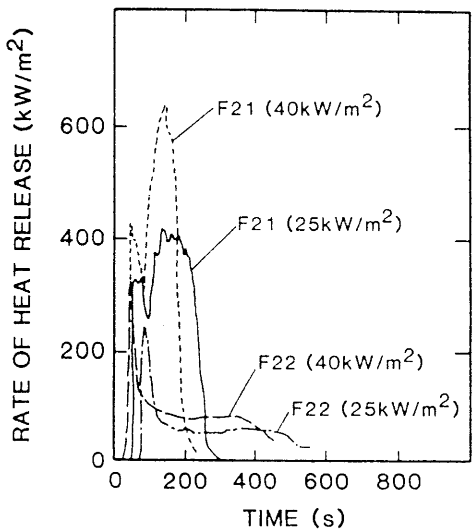

Figure 2. Typical Cone Calorimeter HRR curves for upholstered furniture specimens

Limits to the correlation

The correlation given above was derived from a study of domestic furniture. The furniture (with the exception of neoprene specimens, which were excluded from the correlation) was only modestly, if at all, fire retarded. All of the specimens spread flame throughout and burned substantially to completion. The full-scale heat release rates were generally over 400 kW. Such behaviour is not typical for institutional furniture. Institutional furniture may be designed to limit spread of flame, so that the full item does not get involved. It is readily seen that since the correlation given in Eq. 1 uses the total combustible specimen mass, if the behaviour is limited to scorching around the ignition source area, with no propagation beyond, such a correlation will not be applicable.

To generalize to the complete range of possible behaviours, we look at Fig. 3. In this schematic figure we see two basic regimes. For high $\dot{q}''_{bs}$ values (the regime marked as 'propagating fires'), the peak full-scale $\dot{q}$ is directly proportional to a product of $\dot{q}''_{bs}$, and the mass, frame, and style factors, as explained above. For low $\dot{q}''_{bs}$ values (the 'non-propagating fires' regime), neither the mass nor the frame nor the style factors have any effect. The reason is that the fire does not grow to such an extent as to burn up the bulk of the mass of the chair, or its combustible frame. The transition between the two regimes will depend on the size of the ignition source used. Specific numbers are provided in the next section for only one illustrative case, an ignition source which corresponds to the California T.B. 133 test.

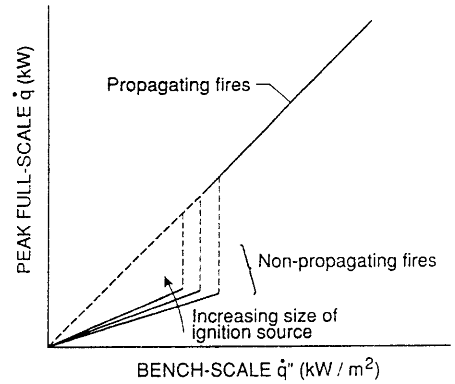

Figure 3. Conceptual relation between non-propagating fires and propagating fires (the correlation line for the latter also depends on specimen mass, frame type, and style, but this is not indicated in the figure). The transition region occurs at $\dot{q}''_{bs} \approx$ 100 to 150 kW/m^2.

For the purpose of setting a lower limit to $\dot{q}''_{bs}$ values for which the predictive correlation of Eq. 1 is applicable, it is appropriate to use about 100 to 150 kW/m^2, with lower HRR specimens being predicted as described in the section on Highly Fire-Retarded Furniture. An exact value within the 100 to 150 kW/m^2 range is not determined; it will depend on ignition source characteristics and other factors not yet quantified.

Predicting the shape of the full-scale HRR curves

During the NIST studies of domestic upholstered furniture, it was observed that the full-scale furniture calorimeter HRR curves had a characteristic shape. Except for those specimens showing a peak of less than about 400 kW, the curves were distinctly triangular. Figure 4 shows a typical measured curve, along with a simplified, triangular representation. It was further found that a simple method could be evolved to predict the base width, t_b, of the triangle. The t_b is, of course, all that was needed additionally, since a method for peak height was already established (Eq. 1).

The predictive method gives that

$$t_b = \frac{C_3 m \Delta h_c}{\dot{q}_{fs}} \tag{4}$$

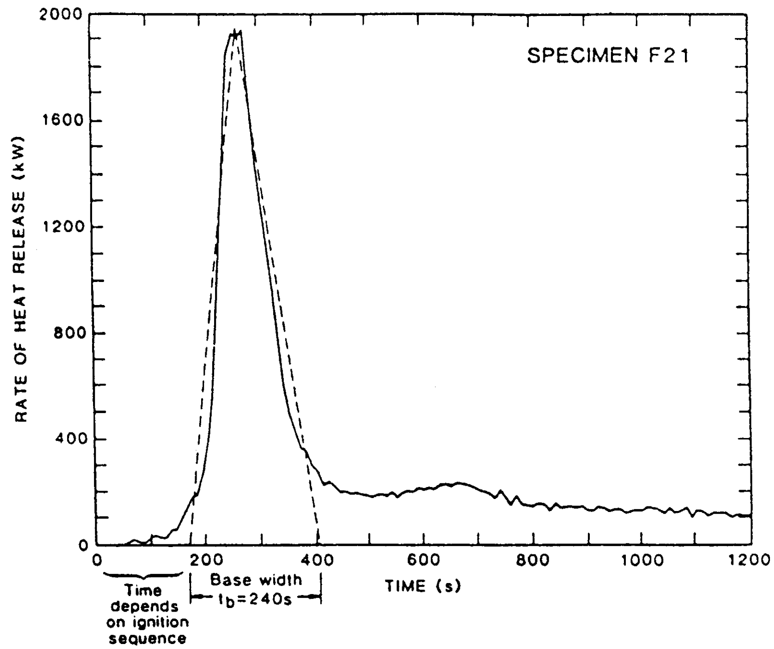

Figure 4. Triangular representation (dotted line) of the measured HRR (solid line) of a full-scale test specimen

where t_b is the base width (s), m is the combustible mass of the specimen (kg), $\dot{q}_{fs}$ is the peak full-scale HRR obtained from Eq. 1, Δh_c is the effective heat of combustion (MJ/kg), and C_3 is defined as

$$C_3 = \begin{array}{l} 1.3 \textit{ for wood frames} \\ 1.8 \textit{ for metal frames and plastic frames} \end{array} \qquad (5)$$

The appropriate value of the effective heat of combustion can be determined from Cone Calorimeter tests.

For most fire modelling purposes, such a triangular description of the specimen's burning is sufficient, even though the 'induction period,' that is, the time from start of test to the start of the t_b period is not determined. This induction period is very strongly associated with the ignition source and scenario used and is not in any sense a material property of the specimen. By contrast, both $\dot{q}_{fs}$ and t_b are generally independent of the ignition sequence, provided only that the ignition is strong enough to ensure spread of flame throughout the specimen.

For more FR types of specimens, the triangular burning shape is not observed, as discussed below.

FURNITURE OF INTERMEDIATE FIRE BEHAVIOUR

When considering fire performance, the upholstered furniture market is often divided into two classes, 'domestic' and 'contract'. Regulatory control of upholstered furniture has largely been applied to 'contract' seating, particularly where it is designed for use in public areas or institutional buildings. But in the U.K., central government regulations [9] have been enacted which control the fire performance of domestic furniture. These controls began in 1980 with cigarette ignitability tests, but in 1989 they were extended to include limits on the post-ignition burning behaviour of the infill materials, followed by a further requirement introduced in 1990 [10] requiring match flame resistance for all covering fabrics. These U.K. regulations brought about a second category of upholstered furniture, whose fire behaviour is measurably better than that of the domestic furniture available in most countries, but is not sufficiently resistant to pass the fire tests for contract furniture. This type of furniture could therefore be considered as having 'intermediate' fire behaviour.

U.K. domestic upholstery requirements

In addition to ignitability requirements for the covering materials (cigarette and match flame according to BS 5852 Part 1 [11]), infill materials are required to meet a mass loss requirement following application of a larger source. The details of this test follow the BS 5852 Part 2 [12] procedures. A test specimen is prepared using the infill and a standard FR polyester cover, intended neither to protect the infill nor to add to the severity of the burning. In the case of polyurethane foam, a wood crib designated in BS 5852 Part 2 as ignition source No. 5, is used. Other infill materials, such as fibres or latex foams, are tested using the weaker No. 2 gas flame ignition source, described in BS 5852 Part 1. In all tests, the specimen must not lose more than 10% of its mass after the test, with additional requirements being placed against flaming drops, glowing and smouldering.

To meet these requirements, U.K. furniture manufacturers use a category of PU foams described as 'combustion modified' (CM) or 'combustion modified high resilience' (CMHR) foams. Most of these foams include a melamine additive, although one manufacturer produces a foam with graphite as the F.R. additive. It should be noted that the term CMHR is used in the U.S.A. to describe more fire-resistant foams, often containing hydrated alumina as an FR additive. In this Section the term is used to describe only the U.K. types.

Heat release rate characteristics

Although the test required in the U.K. regulations does not measure heat release rate directly, Rogers and Ames [13] carried out measurements on the new materials and those they replaced. Measurements were made originally using the

Table 1
Full-scale and bench-scale data on chairs tested at FRS

Cover and foam type		Specimen mass (kg)	Full-scale Peak HRR (kW)	Bench-scale Peak HRR (kW/m^2)
FR PE	STD1	2.7	370	302
FR PE	STD2	2.1	350	342
FR PE	STD3	1.4	401	392
FR PE	STD4	2.3	600	415
FR PE	STD5	2.6	400	335
FR PE	STD6	2.8	322	415
FR PE	STD7	2.2	199	229
FR PE	STD8	3.0	513	364
FR PE	CM1	2.8	40	229
FR PE	CM2	2.1	69	201
FR PE	CM3	3.8	102	162
FR PE	CM4	2.9	110	182
FR PE	CM5	2.2	74	209
FR PE	CM6	2.8	35	250
FR PE	CM7	2.5	33	174
FR PE	CM8	2.8	186	267

FRS buoyancy driven, chimney type furniture calorimeter (see Chapter 5). Measurements were also made using the bench-scale Cone Calorimeter and a NORDTEST NT FIRE 032 type furniture calorimeter[2], which was subsequently installed at the FRS.

A range of 16 infill/cover combinations were initially selected to represent the complete range from unprotected domestic types to the most resistant institutional furniture. This was followed by the testing of a range of 8 new CM/CMHR foams together with 8 standard or high resilience (HR) foams manufactured by the same companies. All of the combinations were tested using the buoyancy furniture calorimeter in the form of a mock-armchair, and standard composite specimens of infill and cover in the Cone Calorimeter. The peak heat release rates obtained are shown in Table 1 and a scatter diagram showing the relationship between

[2] Note that the *procedure* used in these tests was not the same as is outlined in NORDTEST NT FIRE 032 and described later in this Chapter. The FRS tests were on single-chair, not sofa-sized mockups and used a T-head gas burner, as described in [6], and not the wood crib used by NORDTEST.

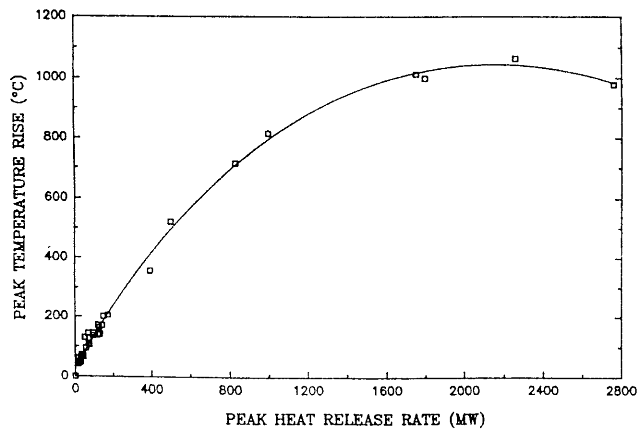

Figure 5. Temperature Rise vs. Heat Release Rate for T.B. 133 and AST Rooms

bench-scale and full-scale peak rate of heat release is shown in Fig. 5. T irradiances used in the Cone Calorimeter measurements were 35 and 50 kW/n The best correlation with full scale (0.93) was achieved using 35 kW/m^2.

Studies at FRS are still going on in this area, and no proposal for replaci present regulations with ones based on HRR has yet been made.

HIGHLY FIRE-RETARDED FURNITURE

Furniture sold for use in institutional occupancies in the state of California mı pass the California Technical Bulletin 133 test (T.B. 133) [14]. Other stai have also begun to adopt this test. The discussion of the heat release rate highly fire-retarded furniture in this chapter is based largely on an extensi investigation of T.B. 133 being carried out jointly by NIST and the Califorı Bureau of Home Furnishings (BHF) [15]. The T.B. 133 fire test is conduct in a room 3.7 m by 3.0 m by 2.4 m high, lined with gypsum board. The furnitı is located on a weighing platform in the rear corner farthest from the doorwa The ignition source is five double sheets of loosely crumpled newsprint plac at the back of the seat and confined by a wire-mesh cage. Temperatures, (concentration, smoke opacity, and mass loss are measured during the test. For ı purpose of this investigation, instrumentation was added to measure the hı release rate by oxygen consumption.

Ten sets of chairs were tested at NIST and at BHF. These were of pla rectilinear construction with wood frames. Only the type of fabric, type of fo and the presence or absence of a fibreglass interliner were varied between ı chairs. The fabrics included wool, nylon, polyolefin and PVC vinyl. The foams examined were a fire-retardant treated polyurethane that passed the California Bulletin 117 bunsen burner and cigarette tests and a more highly FR melamine-treated polyurethane. The chosen combinations which provided a very large range of fire performance are listed in Table 2. The total heat release rates were measured in the NIST furniture calorimeter (described in Chapter 5), the ASTM room fire test and the room fire test specified in T.B. 133. The ASTM room refers to the proposed ASTM room fire test (also described in Chapter 5), which is conducted in a 2.4 m by 3.6 m by 2.4 m high room, lined with calcium silicate board. The newspaper ignition source specified in T.B. 133 and a propane burner used to simulate it [16] were each used to ignite these chairs. The heat release rate per unit area and the heat of combustion were measured in the Cone calorimeter for each of the 10 combinations of materials.

One of the failure criteria in the T.B. 133 is the achievement of a 111°C air temperature rise at a thermocouple located 25 mm below the ceiling and directly above the ignition source. Figure 6 shows the peak temperature at this location for each type of chair, plotted against its peak heat release rate in the T.B. 133 and ASTM rooms. This curve provides a method of establishing an equivalence between the heat release rate and the temperature rise above the chair for these particular rooms. It can be seen from an expansion of Figure 5 that a failure temperature of 111°C in the T.B. 133 room is equivalent to a heat release rate of 65 kW. In re-defining the T.B.133 in 1990-1991 (see below), however, the State of California selected a 'passing' HRR value of 80 kW. This was done to allow

Table 2
Materials used in the test program for highly-FR furniture

A. Wool Fabric California 117 Foam	B. Wool Fabric Fibreglass Interliner California 117 Foam
C. Nylon Fabric Melamine Foam	D. Nylon Fabric Fibreglass Interliner Melamine Foam
E. Nylon Fabric California 117 Foam	F. Nylon Fabric Fibreglass Interliner California 117 Foam
G. PVC Vinyl Fabric California 117 Foam	H. PVC Vinyl Fabric Melamine Foam
I. Polyolefin Fabric Fibreglass Interliner California 117 Foam	J. Polyolefin Fabric California 117 Foam

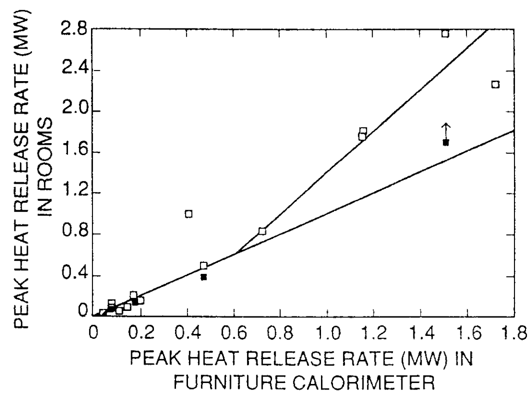

Figure 6. Heat Release Rate in Rooms vs. Heat Release Rate in Furniture Calorimeter

for any scatter in the existing data correlation. Thus, highly fire-retarded furniture is nowadays often regarded as furniture having a heat release rate of less than 80 kW based on the T.B. 133 criteria. Because of the limited fire spread on chairs that pass T.B. 133, the peak heat release rate is not as dependent on chair size as it would be for the moderately fire-retarded or the conventional classes described in the earlier sections of this chapter. On the other hand it is dependent on the details of the ignition source for highly fire-retarded furniture.

When a chair is burned in a room there is some thermal radiation reinforcement from the walls, the ceiling and the hot gas layer. This increases with the total heat release rate of the chair. The heat release rate at which the reinforcement becomes significant may be expected to depend on the size of the room and the thermal properties (conductivity, specific heat and density) of the lining materials.

The rooms used in this investigation were lined with calcium silicate board or gypsum board and the floor area was 9 or 11 m^2 with an open doorway. The total heat release rates in the T.B. 133 and ASTM rooms are plotted in Figure 6 against their open-burning heat release rates, as measured in the furniture calorimeter for all of the chairs tested. The heat release rates were measured by oxygen consumption in both cases. The data fall close to the equality line until 600 kW is reached. This is about half of the heat release rate required to produce flashover in these rooms. Since highly fire-retarded furniture, as defined in this Section, has peak heat release rates less than 80 kW, the heat release rates measured in the furniture calorimeter apply equally well to fires in rooms.

One of the advantages of knowing the heat release rate in a room is the ability to predict the temperature in the room of fire origin and in the rooms beyond. The heat release rates measured in the ASTM room were used in the computer program HAZARD I [17] to calculate the temperature histories of the upper layer for all ten chairs. The peak calculated values are compared with the peak measured values in Figure 7. The temperatures were measured with an 0.12 mm diameter thermocouple, located 100 mm below the ceiling at the centre of the room. Except for Chair E, the points fall close to the equality line. Chair E had a considerably higher heat release rate than any of the other chairs but a significant fraction of the burning took place outside the room. The calculations performed with HAZARD I assumed all of the heat was released inside the room. The effect of the increased rate of pyrolysis was to decrease the temperature due to dilution. This figure demonstrates once again the strong relationship between the heat release rate of the chair and the temperature of the upper air layer near the ceiling of the room.

In general, the total heat release rate curves of upholstered furniture have two major peaks, one representing the burning of the fabric and one the burning of the underlying foam or padding. For highly fire retarded or institutional furniture, the foam does not get involved and so there is only one peak. For domestic furniture, as seen in Figure 4, the foam becomes involved so quickly that the two peaks merge into one. For moderately fire-retardant furniture, the two peaks are resolved and the separation between them can be quite large as seen in Figure 8. In some cases the foam may smoulder for over an hour before it flames, producing the second peak long after the fabric burning has stopped. The actual HRR curves can exhibit additional peaks, due to other phenomena such as collapse. These peaks are much more difficult to predict and are not discussed further here.

As with the domestic furniture described above, it would be desirable if the full-scale HRR behaviour of the highly-FR furniture could be predicted from bench-scale Cone Calorimeter measurements. The peak heat release rates of the chairs in the furniture calorimeter were compared against the 180-s average heat release

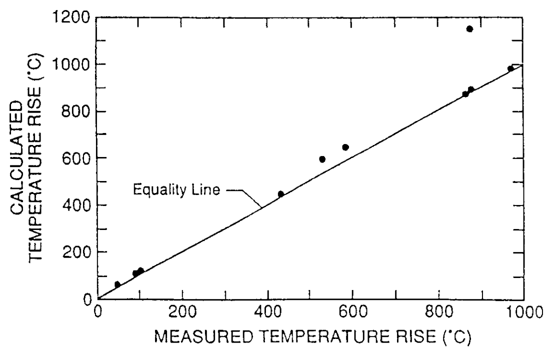

Figure 7. Calculated Temperature Rise Using Hazard I, compared against experimental results

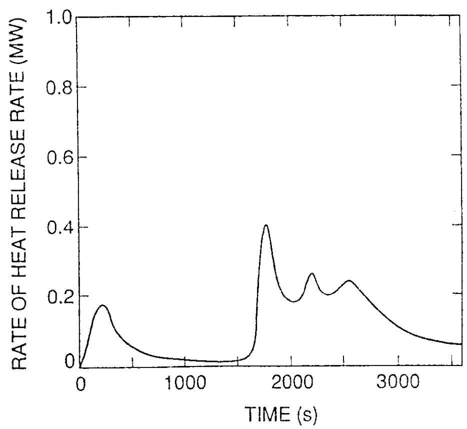

Figure 8. Heat Release Rate of Chair F in the Furniture Calorimeter

rates of the material combinations in the Cone Calorimeter at an exposure level of 35 kW/m^2. The 35 kW/m^2 test irradiance is as specified in the new NFPA 246A standard for the use of the Cone calorimeter for upholstered furniture [18]. The results are shown in Figure 9, where the letters beside the points indicate the code letter for the chair. For bench-scale heat release rates below 180 kW/m^2 the data points fall on one straight line while above 180 kW/m^2 they fall on a different line. The lower correlation line represents fabric peaks, while the upper line represents foam, or merged fabric+foam peaks. The fabric peaks are lower because the fabric generally has less fuel per unit area and the area of involvement is usually smaller. Chairs B, D and H represent the highly FR materials that are the topic of this section. Chairs I, F and G are moderately FR chairs. For these chairs, two peaks were correlated, the primed letters on the

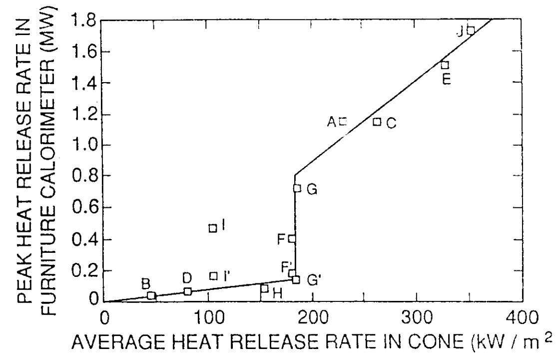

Figure 9. Highly FR furniture: correlation between bench-scale and full-scale HRR measurements

graph representing the first or fabric peak and the un-primed letters I, F and G representing the second or foam peak. The lines are represented as:

Highly FR chairs (including the first, fabric peak of moderately FR chairs)

$$\dot{q}_{fs} = 0.75\,\dot{q}_{bs}'' \tag{6}$$

Conventional chairs (including the second peak of moderately FR chairs)

$$\dot{q}_{fs} = 4.7\,\dot{q}_{bs}'' \tag{7}$$

Two *caveats* should be noted for the above equations. The Eq. 6 correlation is dependent on the details of the ignition source and its location; the relation given applies only to the source used for California T.B. 133 testing. The Eq. 7 correlation is not a general predictive equation; it works only because the test chairs plotted in Fig. 9 had nearly identical mass, frame, and style factors. With this in mind, it would be appropriate to compare the data from these same test chairs against the general predictive relationship for conventional furniture, as given in Eq. 1. Such a comparison cannot be derived precisely, since Eq. 1 was derived for the condition of irradiance = 25 kW/m^2, whereas the tests on highly fire-retarded specimens were conducted at 35 kW/m^2.

Even though an irradiance of 35, rather than 25 kW/m^2 was necessary for conducting the bench-scale tests in highly-fire-retarded specimen series, it is still possible to use the predictive results of Eq. 1 if allowance is made for the different irradiances. If it is assumed that the heat release rate in the Cone calorimeter is directly proportional to the external radiant flux then the coefficient 0.63 in Eq. 1 could be replaced by $15.75/q_{ext}$. Table 3 shows a comparison of the full scale test results in the furniture calorimeter with the predicted heat release rates using an external flux of 35 kW/m^2 in the modified version of Eq. 1. This equation is intended to predict the burning rate of chairs in the furniture calorimeter, which involve propagating fires. Non-propagating fires are so identified in Table 3. The comparisons with these chairs clearly show the errors which could arise due to misuse of this equation. With the exception of Chair F, the remainder of the chairs are predicted within 20 percent and the rank ordering is essentially the same for the predicted and measured values. The reason for the very low measured heat release rate for Chair F is not understood. It should be noted that the heat release rate of Chair F in the room fire test was 1000 kW/m^2. The curve in figure 6 would indicate an expected value of approximately 800 kW/m^2 in the furniture calorimeter, which is in agreement with the predicted value of 780 kW/m^2. The comparisons in Table 3 suggest that the modified Eq. 1 is applicable to Cone calorimeter data which is taken at different fluxes but that

Table 3.
Comparison of Results on Highly-Fire-Retarded Specimens from the NIST/California Test Program against a Modified Version of eqn (1)

Chair	Bench-scale $\dot{q}''$ (kW/m^2)	Mass factor	Frame factor	Style factor	Full-scale (kW)	
					Predicted	Measured in furniture calorimeter
B	46	34	0.30	1.0	335[a]	38
C	264	35	0.30	1.0	1250	1151
D	80	35	0.30	1.0	600[a]	71
E	328	32	0.30	1.0	1410	1510
F	181	32	0.30	1.0	780	403
G	185	34	0.30	1.0	850	720
A	231	32	0.30	1.0	1000	1156
H	154	38	0.30	1.0	1250[a]	75
I	105	33	0.30	1.0	470	467
J	352	31	0.30	1.0	1470	1720

[a] non-propagating fire in full-scale
[b] post-flashover, ventilation-limited fire

it should not be used for highly fire-retarded furniture represented by Chairs B, D and H.

For compliance with the State of California limit of 80 kW, it can be seen that Eq. 6 implies that $\dot{q}_{bs}''$ value of < 107 kW/m^2 is required. For practical application of bench-scale Cone Calorimeter results to establishing equivalency to the full-scale result, this would most likely be rounded down to 100 kW/m^2.

Finally, some guidance can also be provided on thermal radiation from chair fires. This is important since the spread of fire from one upholstered chair to a chair not in intimate proximity depends on the thermal radiation. The radiant heat flux measured 0.76 m from the chair is plotted as a function of the peak heat release rate of the chair in Figure 10. It is seen to increase linearly with the total heat release rate according to the formula:

$$\dot{q}_{flux}'' = 0.011\,\dot{q}_{fs} \tag{8}$$

where $\dot{q}_{flux}''$ is the heat flux in kW/m^2. A radiant flux of 10 kW/m^2 represents a practical lower limit for piloted ignition of materials. Hence, radiant ignition at

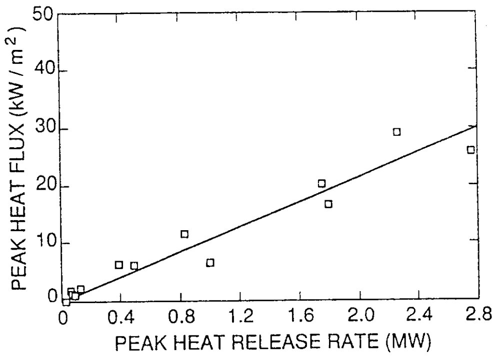

Figure 10. Radiant Flux 0.76 m from Chair

that distance would require a total heat release rate for the burning chair of over 900 kW and would depend on the characteristics of the exposed chair. Also, it can be concluded that chair which successfully pass the T.B. 133 test are not expected to ignite nearby furniture by thermal radiation.

STANDARDIZED TESTS

As mentioned above, there have been a plethora of flammability tests proposed for upholstered furniture. Most of these are Bunsen-burner type of ignition tests and are not relevant to the issues of measuring heat release rate. Only a few tests have been developed which are true heat release rate tests. These we will describe in this Section.

Full-scale tests: NORDTEST Furniture Calorimeter

A standardized test for full-scale furniture items is the NORDTEST furniture calorimeter test, discussed in Chapter 5.

Ignition source

The ignition source[3] is a 126 g wood crib, corresponding to crib no. 7 in the British Standard BS 5852 Part 2 [19]. This crib provides about 6 - 7 kW, for a period of about 350 s. The crib is placed at the end of the seat cushion, and in contact with both the back cushion and the arm rest.

[3] Since both the United Kingdom and the United States have recently been using gas burner ignition sources, NORDTEST are considering a possible revision to the standard which would replace the wood crib with a gas burner.

Specimens

Two types of specimens are provided for: real, full-size, 3-seater sofas; or a full-size sofa mockup. The Standard contains instructions for preparing a metal frame and the appropriate test cushions when the mockup option is chosen.

Results reported

The Standard provides for reporting the following main data:

specimen identification
the complete mass loss rate curve
the complete heat release rate curve
the complete curves for the production rate of CO, CO_2, and smoke
the complete curve for the mass flow rate in the exhaust duct.

Criteria

The method, as published, contains no criteria for pass/fail or classification into performance categories. Criteria will presumably be established by user bodies.

Full-scale Tests: Underwriters Laboratories Furniture Calorimeter

In principal, the Underwriters Laboratories Fire Test of Upholstered Furniture (UL 1056) [20] is very similar to the NORDTEST one. A furniture calorimeter is used which has a flow rate of at least 0.47 m^3/s and an exhaust duct diameter of approximately 0.41 m. Unlike the NORDTEST method, however, smoke, CO, and CO_2 are not monitored.

Ignition source

The ignition source is a wood crib of 340 g mass, substantially larger than the one in the NORDTEST method. This crib burns at about 15 kW for 180 - 210 s. The crib is placed at the centre of the seat cushion, 25 mm away from the back cushion.

Specimens

Unlike the NORDTEST standard, the normal specimen is a single-seat chair; no provisions for mockup testing are made.

Test conditions

The test is continued only for a total of 10 min after ignition (specimens which show continued active combustion at this time would have failed the test criteria).

Results reported

The results reported are:

the complete curve of the heat release rate
the peak heat release rate
the total heat released during the first 5 minutes of test
the heat release rate and the mass loss, tabulated at 5 s intervals.

Criteria

The specimen passes if the total heat released during the first 5 minutes of test do not exceed 25 MJ. (This is equivalent to a 5-min average HRR of 83 kW). The low value of HRR required to pass the test makes clear that the method is intended only for institutional and high risk applications.

Full-scale tests: California T.B. 133

Until 1990 the California T.B. 133 test did not have provision for HRR measurement. As a result of the cooperative NIST/California program discussed above, however, the test was revised in June 1990 and again in January 1991 to provide for either HRR-based measurements or the previous instrumentation (thermocouples, smoke meter, load cell, and CO analyzer). In either case, the ignition source comprising newspapers in a wire basket was replaced by a burner source. The previous ignition source is now permitted only as a screening test.

Test room

The prescribed room is 3.7 × 3.1 × 2.4 m high, with doorway 0.97 × 2.06 m high. As an alternative, the ASTM room is also allowed. If the option of using HRR-based criteria is selected, then the test, as an alternative, may be conducted in a furniture calorimeter.

Thermocouples

(a) over the ignition source and 25 mm below the ceiling.
(b) 0.91 m in front of the ignition source and 1.22 m below the ceiling.

Smoke photometer

- at room mid-height, spanning the 3.7 m dimension.
- earlier versions of the standard also required a second photometer, 100 mm above the floor, but this has now been withdrawn.

Gas sampling

Port located near the corner, 165 mm below the ceiling.
Gas measured — CO only.

Load cell: one, for specimen.

Specimen

Full-scale end-use specimen or a full-scale mockup. Mockup frame is 0.91 m long and has a tiltable back (up to 45° back from vertical). The specimen is placed in the corner of the room, "within 254 mm of each wall."

Ignition source

The square gas burner developed during the NIST/California test programme must be used for compliance tests. The previously used wire-basket filled with newspaper may be used only for informal screening tests.

The gas burner ignition source

A hollow-square gas burner is fed with propane at a rate equivalent to 18 kW. The burner is turned on for 80 s. The burner, which is intended to simulate the newspaper ignition source is centrally placed, at 50 mm away from the back cushion and 25 mm above the seat cushion.

The newspaper ignition source

Five double sheets of loosely crumpled newspaper (total mass = 90 g) contained in a box made of galvanized sheet steel and wire mesh. Size is 250 × 250 × 250 mm. Three different variants of the box are provided, one for specimens that have a crevice at the seat/back juncture, one for specimens which do not, and a third one for specimens that, instead, have a gap in that area. For specimens less than 1.0 m long the ignition basket is located centrally, at the seat/back juncture. For longer specimens, it is located at the seat/back juncture and 127 mm away from the left side arm.

Criteria for passing
Must pass all of (A) or (B):

(A)
- Temperature rise < 111 °C at ceiling thermocouple
- Temperature rise < 28 °C at mid-height thermocouple
- Smoke obscuration < 75% at photometer
- There must be no period of 300 s or greater during which CO concentrations > 1000 ppm
- Mass loss ≤ 1.362 kg during the first 600 s of test

(B)

- Peak HRR ≤ 80 kW
- Total heat release ≤ 25 MJ during the first 600 s of test.

Bench-scale tests: Cone Calorimeter

A standard for Cone Calorimeter testing of upholstered furniture composites has been developed by the National Fire Protection Association as NFPA 264A [18]. This method was based on the earlier NIST work described above.

Test conditions

An irradiance of 35 kW/m^2 is specified, since the method is intended primarily for application to institutional occupancies. The specimen is tested in the horizontal orientation, and is ignited with the spark plug.

Specimen preparation

Since composite padding/fabric assemblies are to be tested (and also, potentially, an interliner layer) special instructions are needed so that bench-scale testing specimens could be prepared which are representative of the performance of the full-scale article. Some constructions may have multiple layers of padding, for a total depth of much more than twice the maximum 50 mm specimen depth. Thus, a procedure was established whereby the outer fabric and any internal layers < 8 mm thick are used in their actual thickness. If more than one padding layer needs to be accounted for, then the thickness of such layers is adjusted so that the ratio of the padding layer thicknesses is the same as in the full-scale article, while conforming to the required test specimen depth of 50 mm.

During test, the outer fabric layer must be prevented from curling, pulling, or otherwise behaving in an unrepresentative manner. To accomplish this, not only the top of the specimen, but also the 4 sides are covered by the fabric. To prepare the specimen, a 200 mm by 200 mm square of fabric is cut. Out of this square, a 50 mm by 50 mm square is removed at each corner. The resultant cruciform shape is then placed upon the padding and diagonally stapled along the bottom edges.

For intermediate layers, the normal procedure is to simply cut 100 × 100 mm squares, to be placed underneath the fabric. If, however, in the experience of the testing laboratory, the function of an interliner is to retard fire growth and a specimen, when so prepared, makes this layer ineffective, an alternative procedure is used. With the alternative procedure, the interliner material is cut in the same way as the fabric, so as to protect the four sides of the specimen.

Results reported

The basic result reported from the test is the average HRR for the 180 s period after ignition. Other ancillary measurements are recorded, similar to the ones specified in the ISO and ASTM Cone Calorimeter tests.

Criteria

The method, as published, contains no criteria for pass/fail or classification into performance categories. Criteria will presumably be established by user bodies.

Testing 'real' composites or 'standardized' composites

Numerous studies at various institutions have shown that meaningful results from bench-scale HRR tests cannot be obtained by testing materials alone. In other words, test data taken on upholstery fabrics or on chair paddings alone cannot be used to predict or estimate the behaviour of an actual fabric/padding assembly. The errors in attempting to do such a procedure can be quite serious. For instance, melamine-treated FR PU foam, if tested without any covering fabric, can show a behaviour which is unrealistically better than with any actual fabric applied on top. Given that, an interesting question can be posed. For approximate guidance or regulation purposes, can one test the combinations of actual fabric + standard foam or actual foam + standard fabric and obtain some rough, but useful, data? The question has not yet been definitively answered. However, data collected at NIST on a large number of foam/fabric combinations were examined. The tests were conducted at an irradiance of 35 kW/m^2. The fabrics used were not 'standard,' but were, rather, a wide assortment of commercially available fabrics. From over 50 tests conducted, it was possible to conclude that foam quality can be assessed from Cone Calorimeter HRR results even when tested under random cover fabrics. The test results showed that the majority of the specimens could be categorized in the following manner [6].

Type of foam	Rate of heat release (avg. for 180 s after ignition) (kW/m^2)
ordinary PU	> 280
melamine PU (or British CMHR PU)	< 280
American CMHR PU	< 160
hydrophillic PU	< 85
neoprene	< 45

In the above categorization, ordinary PU refers to both non-FR foams and foams which only pass CAL 117 requirements. The British CMHR ('combustion-modified high resilience') PU are foams which pass the British requirements [21]. The foam most typically available which meets this requirement is one which has been treated with melamine [22],[23]. This is to be distinguished from foams which were promoted some years earlier in the American market. These American CMHR foams were intended for the institutional and not the domestic market, and had a much higher level of treatment with both FR agent and inorganic inert fillers [24],[25], thus showing a higher level of fire performance.

The success with the above categorization suggests that in those applications where the goal is to regulate the padding materials to a particular level of performance, it should certainly be feasible to conduct HRR tests using a standard fabric, and to obtain results which give good guidance. A standard fabric (FR polyester, 220 g/m^2) for testing is already specified in the British regulations [21]. A similar reasoning may be applicable towards the question of distinguishing fabric performance when tested over a standard foam, but data have not yet been presented.

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